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BALL LIGHTNING: NEW OBSERVATIONS AND NEW HYPOTHESES

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ABSTRACT. In publishing new data about ball lightning on the pages of this journal, the editor attempts to attract attention to this phenomenon, which, up to the present time, has not had a generally accepted physical explanation. Difficulties of observation, theoretical interpretation and experimental reproduction of ball lightning must be completely and finally solved. If our publications stimulate further study in this direction, the editor will consider his task fulfilled.

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Recently, a series of literature surveys have been published on the properties of ball lightning(1), which up to the present time have not resolved its secret. New hypotheses have been presented on the nature of this phenomenon: the hypothesis of a superconducting hard substance — a condensate of atoms of nitrogen and oxygen; an adiabatic concentration of macro-ionic formations with closed shells; an ionized toroidal vortex, etc. Successful photographs of ball lightning have been made. Also, studies on artificial production of ball lightning under laboratory conditions have been conducted with an electric probe of long discharge intervals in the air, by excitation of high frequency nonelectrode

*Numbers in the margin indicate pagination in the original foreign text.

**For Biography, see the end of the article, page 24.

(1)For Bibliography, see the end of the article, page 25.

discharges, by bombarding the air with a jet of plasmotrons and plasmoids from plasma guns, by focusing radio waves in small volumes of air, by action of high speed electron flows and laser radiation in the air, etc. In some of these studies, limited success has been attained[(2)]. A number of readers have responded to discussions published in the journal on the nature of ball lightning. Moreover, a great quantity of material has been sent to the editor on recently conducted observations. We shall attempt to analyze and generalize these new data.

In agreement with the hypothesis of a superconducting condensate of nitrogen and oxygen, suggested by G. S. Teletov, ball lightning contains a dense core, the material of which is a metal-like condensate of atoms of nitrogen and oxygen, possessing the qualities of a solid. This core is surrounded by luminescent hot plasma, but the high specific energy of the ball lightning is basically connected with the internal energy of the phase state of this condensate. The core, on the formation of lightning, is closed into a ring and is restrained in the plasma by its magnetic field, if a strong current circulates in it. The longevity of lightning indicates that the material of the ring is undoubtedly /51 in a state of metastability and superconductivity. It is assumed that such ball lightning can be generated by very powerful discharges of linear lightning, resulting from the creation of superhigh pressures in it and the high density of the material at relatively low temperatures. It is assumed that with very great densities of current and magnetic field, metallic conductivity can arise, while with a greater increase in pressure and sufficiently strong generation of the electron state — also a superconductive state can arise in the metal-like condensate. The internal energy of the compressible material, which is necessary for the migration of electrons to high levels corresponding to the electron gas produced in the condensate, is on the order of 1400 kcal/g. When the internal energy of this material reaches such a value, a phase transition occurs — the compression energy can be converted to intratomic energy with an intermittent decrease in volume and some lowering of temperature. Within a certain time after completion of condensation, the direct conductor with a strong current

(2) See Priroda, No. 8, 1968, page 109.

can form a loop as a result of a transverse instability, which then must form a ring. Such a ring must then immediately be enveloped by a plasma, which corresponds to formation of ball lightning. In agreement with this hypothesis, for lightning with a dimension of 20 cm, current amplitude of approximately $5 \cdot 10^7$ A is necessary (such powerful discharges can be very rare). Internal energy of ball lightning amounts to around 1400 kcal/g, and its luminescence is due to the high temperature of the plasma shell.

In agreement with the hypothesis of the macro-ionic formations suggested by the author of the present survey, in gases where stable negative ions exist (particularly in air), an adiabatic concentration of low temperature plasma is possible. Stabilized ball lightning contains plasma of ions of nitrogen, oxygen, nitric oxide and free electrons, surrounded by a closed envelope of negative ions of oxygen and ozone. The envelope is in an electrically fixed state, and therefore possesses increased mechanical stability and low heat conductivity. Formation of ball lightning can occur either upon discharges of linear lightning (when part of the channel, cooled after discharge, is constricted by the envelope and changes to a spheroid) or upon other electrical processes in the atmosphere. The plasma of ball lightning is significantly lighter than air, but its average density is close to the density of air, due to the presence of a cold, dense envelope. In this connection, one may expect ball lightning to be capable of freely floating in air for a certain length of time, subject to electrostatic influences, to shifts in the wind, etc. Lightning plasma has a certain store of energy, which is liberated during the processes of ion recombination, basically in the form of optical radiation. The duration of lightning can vary, but it is limited by its energy resources. Thus, in ordinary air, ion concentrations on the order of 10^3 per 1 cm^3 exist approximately ten minutes. Lightning emissions can pulsate and in time cease, while the frequency of pulsations must grow with the spontaneous disappearance of lightning. Thanks to this energy source, lightning can autonomously shift as a result of the reactive effect, caused by the preeminent recombination of ions in some one part of the lightning. Under an external influence, a thrust may develop in a direction opposite to the wind or air flow (in flues).

In accordance with calculations, lightning with a diameter of 10 cm has an energy store of about 150 cal, or 3.5 kkal/g (disregarding material of the envelope). The total charge of such lightning amounts to approximately 20 coulomb, since the charge of one sign is not equal and constantly changes as a result of corona discharge (even the lightning potential simultaneously changes, reaching several million volts). Lightning can be set off by an electrochemical mechanism, analogous to the explosion of detonating gas, with the difference, however, that, instead of hydrogen, ions of nitrogen participate in the reaction and the outburst is stronger. With regard to the outburst power, ball lightning with a diameter of 10 cm can correspond to an explosion of from one hundred to several hundred kilograms of ordinary explosive material. Products of such an explosion are nitric oxides, such as occur in the reaction of nitrogen ions with oxygen. Experiments on bombarding air with electrons, the energy of which gradually increases, also attest to the close bond between the burning of introgen in oxygen and possible electrical processes in ball lightning. Nitrogen begins to react with oxygen, forming nitric oxide, only after the electron energy reaches 15.6 electron volts — that is, the ionization potential of nitrocular nitrogen. With further ionization of nitrogen, its burning speed constantly increases (Figure 1)[3].

In the opinion of D. A. Frank-Kamenetskiy, the hypothesis of macro-ionic formations is closer to the usual concept, as compared to the foregoing.[4] D. I. Kulagin, considering the hypothesis of macro-ionic formations of limited interest, indicates that ball lightning as a whole is neutral to a large degree (that is, it does not have a significant charge of one sign), while the principal means of liberating its energy is recombination of ions. Since generation of ball lightning, according to this hypothesis, occurs in atmospheric processes connected with ionization of air molecules, as Kulagin notes, its formation, in addition to the primary activity of thunderstorms, snow storms and snow showers, can also cause sand storms and ordinary rains.

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[3] See M. T. Dmitriyev. On Primary Ions Causing Radiation Oxidation of Nitrogen. Zhurnal Fizicheskoy Khimii, Vol. 40, No. 8, 1966, p. 1739.

[4] Priroda, No. 9, 1966, page 84.

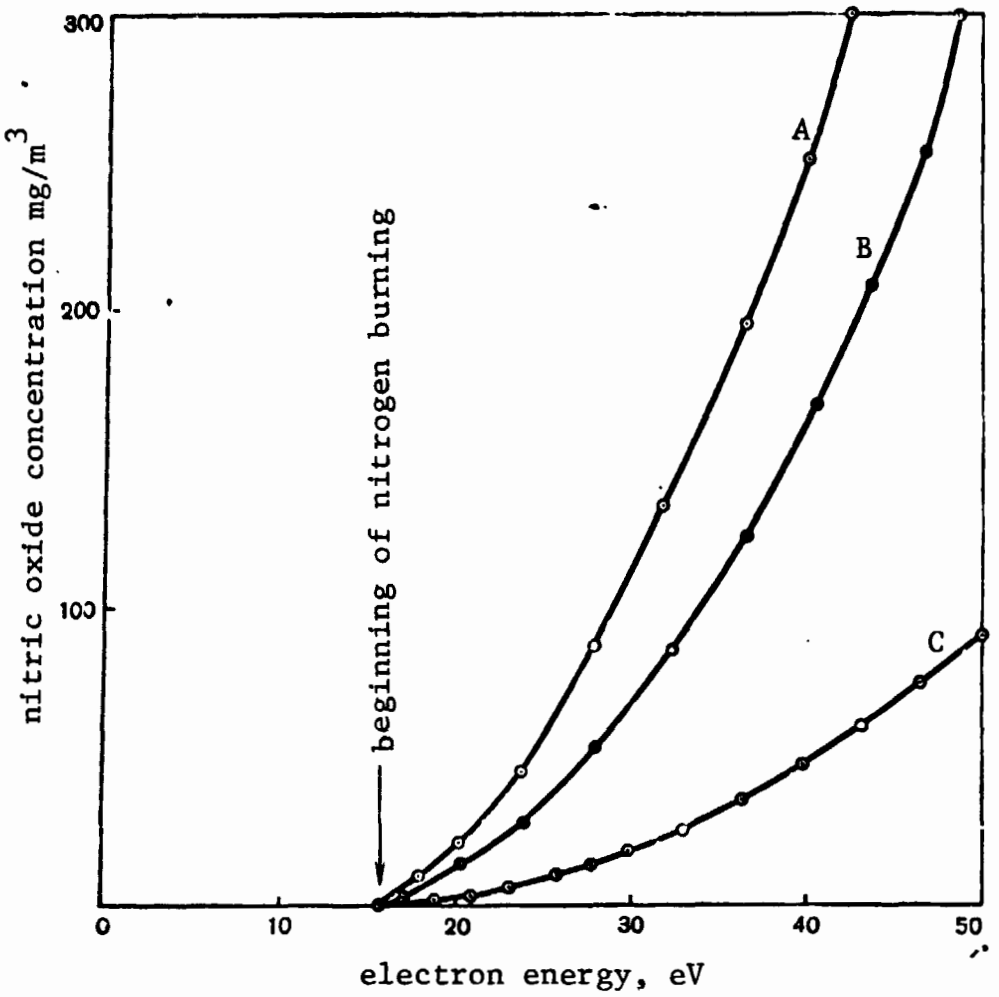

Figure 1. Dependence of nitric oxide concentration in the air and nitric oxide admixtures on the energy of electrons. Burning of nitrogen begins to occur after its ionization.

A - composition; B - air; C - 5% nitrogen in oxygen.

V. A. Gubichev, propounding the hypothesis of an ionized toroidal vortex, /52 considers it primarily necessary to clearly separate the phenomenon of ball lightning from others, which are externally similar to it, and unlike the hypothesis of macro-ionic formations, suggests considering ball lightning as only ball-shaped objects, appearing as a result of the discharge of linear lightning. Taking a stand against the hypothesis of a superconductive condensate, V. A. Gubichev considers its weak point is the necessary formation of ball lightning of superpowerful electrical discharges, with current force of above 50

million amperes, which exceeds the recorded value of the most powerful discharges (0.2 million amperes) by many hundred times. The hypothesis of a superconductive condensate is also in disagreement with obtaining ball lightning at small currents under laboratory conditions, although these experiments are not always reproducible.

In the opinion of V. A. Gubichev, ball lightning can arise upon the action on linear lightning of a shock wave from other lightning (or from another channel of the same lightning). The channel of lightning may be set off even before complete cessation of current in it, and positive ions scattered from the channel will intertwine with the residual magnetic field. As a result, a toroidal vortex with adequate concentrations of ions will be formed. A charged toroid, stabilized by vortex movement, can shine for a certain period and will be externally similar to a sphere. Excited ions, especially atomic ions of nitrogen, and the reaction of excited atomic ions, during which ions of nitric oxide are formed, and other stable combinations play an essential role in illuminating the interior portion of lightning. Externally, lightning must shine with a bluish-lilac corona discharge (which is ordinarily accompanied by hissing and crackling) caused by the potential of the lightning charge. With a current density of corona discharge of 20 $\mu A/cm^2$, a lightning charge with a diameter of 20 cm must amount to 1.5 coulomb if it is to last one minute. A charge of even 0.1 coulomb is sufficient for generation of the corona discharge. It is assumed that density of the air in an ionized vortex with temperatures on the order of 20,000° K can amount to 1 g/cm^3 and higher; that is, ball lightning must be significantly heavier than air, and the energy contained in it must be equal to 15 kcal. After loss of the charge, the energy of lightning (corresponding to the energy of the vortex motion) amounts to 2 - 3 kcal. V. A. Gubichev suggests attempting to obtain ball lightning by experiments with long discharges when shock waves act upon them.

V. A. Gubichev points out two cases, described in the literature, which support his hypothesis of an ionized toroidal vortex, formed under the action of shock waves in a channel of linear lightning. On 20 August, 1889, near

Kherson, ball lightning with a diameter of approximately 10 cm was emitted from clouds in a vertical, downward direction, while a "somewhat depressed center was noted within the lower part". Upon nearing a telegraph pole with a lightning rod, the ball began to lengthen. Then a sharp explosion followed, and sparks scattered on all sides of the lightning rod (the event was described by P. Zelen). In another instance, which occurred August, 1895, at Rostov na Don, ball lightning with a diameter of approximately 10 cm, located on the ground, suddenly involuted and then with a crack dissipated, leaving a sharp smell (described by Koltanovskiy).

A. Dauvillier[5] assumes that ball lightning generally does not have an electrical nature. In the opinion of this author, physical qualities of observed ball lightning indicate it is not the product of thunder clouds, but the result /53 of a sandstorm or tornado. Making air move at high speeds by ultracentrifugation or in a supersonic wind tunnel, in the opinion of Fovil'ye, makes it possible to reproduce ball lightning without electrical means.

C. M. Cade[6], analyzing several observations on ball lightning, in which there were significant human losses (dozens of men were killed and about one hundred injured), considers the distressing idea of creating artificial ball lightning as a new type of weapon.

Among the various hypotheses offered recently, there is practically nothing in common, as a result of which, the nature of ball lightning as before remains unclear. Relative to the energy of ball lightning, values of various orders are cited — from 3.5 to 1400 kcal/g (according to the well-known evaluation of B. L. Gudlet, made when ball lightning hit a vat of water — approximately 3 kcal/cm^3). The density of the lightning material, according to these hypotheses, is assumed to be different — from the density of air to 1 g/cm^3 and higher. It is obvious that along with theoretical observations, laboratory

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(5) A. Dauvillier. Comptes rendus de l'Academie des sciences, Vol. 260, No. 6, 1965, page 1707.

(6) Cade, C. M. Discovery, No. 2/6, 1962, p.23.

research will be of fundamental importance for solving the nature of this phenomenon. Constant elevation in the cultural level of the population along with the enormous territories of our country more and more facilitate the accumulation of material. A definite role will also be played by international cooperation, in this regard. Collection of materials on ball lightning with distribution of information is a function of the recently created Center on Rapid Natural Phenomena at the Smithsonian Institute in Cambridge (Massachusetts, United States). The Soviet Geophysical Committee of the Academy of Sciences of the USSR is a recipient of information from this center[7].

In "Priroda", the interesting experiments of J. D. Barry[8] are described in detail. It was established that under the action of electrical discharges, realized with the assistance of a simple device, in air containing $\sim$ 1.4 - 1.8% propane, at atmospheric pressure, shining balls with a diameter of several centimeters are formed, which exist after cessation of the discharge up to two seconds. Undoubtedly, this is very important work, although cases of sporadic appearances of shining balls under the action of random electrical discharges, closed in a contaminated atmosphere of submarines or warehouses, were described even earlier. It cannot be denied that similar phenomena occur even under natural conditions over marshy or populated regions. However, in pure air the concentration of hydrocarbon does not exceed 1.2 mg/m^3; that is 32.5 thousand times lower than in the Barry experiments. Thus, it is still impossible to state that natural ball lightning is reproduced under laboratory conditions. The greatest interest is naturally given to photographs of ball lightning. We recently obtained photos with the help of modern optical apparatus.

V. M. Deryugin, after making several thousand photographs of ordinary lightning at nighttime, obtained a successful photograph of ball lightning (Figure 2) photographed by him on 9 June, 1938, at approximately 29 hours 30 minutes, at the hydrometeorological station of Karabau in Kzyl-Kuchinskiy region,

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(7) See Priroda, No. 3, 1970, page 118.

(8) See Priroda, No. 8, 1968, page 109; No. 12, 1969, pp. 62-64.

Figure 2. Ball lightning, observed 9 June 1958 in Gurevskaya oblast:

To the left — general view of the place of observation; reflection of linear lightning and trace of ball lightning is seen on the water;

To the right — a trace of ball lightning on a large scale.

The photo was made by V. M. Deryugin with a "Moskva 2" camera on a film with sensitivity of 65 units GOST. The shutter of the apparatus was opened during the exposure and released after observation of the lightning.

Gurevskaya oblast. In the photo, reflection of a flash of linear or plane lightning, as well as a trace of ball lightning is seen on water. In observing the lightning trace, visible in the background of the water reservoir shore, it is possible to reach the following conclusions. If one considers that the reflection of plane lightning was momentary, then luminescence from

the ball is relatively small. The trace of ball lightning on its two rectilinear parts has one and the same thickness and broadens only in places where the direction of lightning motion changed continuously. This undoubtedly indicates that the lightning had a true spherical form. In the photo it is apparent (especially in the second rectilinear part toward the top) that luminescence of the lightning changed at approximately equal time intervals, or at intervals during the course of its motion. Four such pulsations are fixed; the frequency of pulsation per diameter of lightning of approximately 10 cm could amount to 5 cps. In the first rectilinear part, lessening of luminescence is comparatively small. On the second part, it is rather significant, and on the third part, the lightning practically dies out entirely. Later, the lightning flared up again and then died down, after which it disappeared entirely. As D. A. Frank-Kamentskiy noted, this photo is of considerable interest.

A successful photo of ball lightning was made by scientific associate of the Bucharest Aerological Observatory, Ya. Dushelivich, on 24 August 1956, 20 hours 15 minutes, at the meteorological station near the mountain pass Predial in the Carpathians (Figure 3). It is noted that after lengthy hot, dry weather, on August 24 during the entire day it was cloudy (Sc, Ns), and there was light rain. Toward evening, great cloud banks (Cb) appeared, and then from 19 hours 30 minutes until 20 hours 30 minutes, heavy thunder storms passed through, shifting from southwest to northeast. Thus, ball lightning was observed for a short period, until the end of the storm. According to testimony of B. L. Dzerdzevskiy (who on that day was several hundred kilometers from the observation point) as a result of the invasion of a cold front, a surging cyclone developed, intensified by the influence of the mountain ridges. The complexity of topography of the ground surface permitted local intensification of the rising torrents, which assumed the character of "up thrusts" in many places. Therefore, with strong unceasing rain, still stronger local showers — in some places accompanied by thunder — occurred in some places.

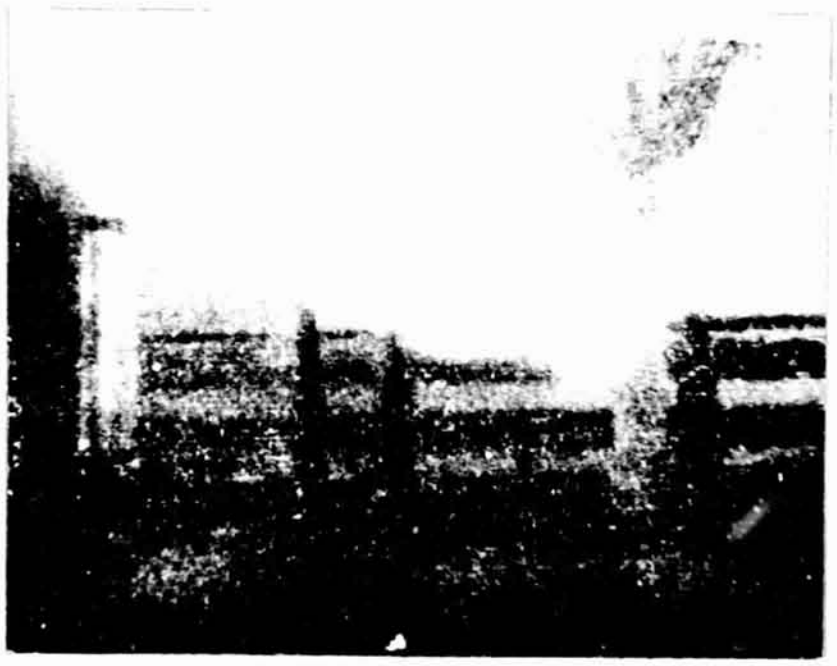

Figure 3. Ball lightning observed in the summer of 1956 during a heavy thunder storm over the meteorological station Predyal in the Carpathians (photo by Ya. Dushelevich).

Ball lightning undoubtedly also occurred during some such thunder storms [9].

By careful analysis of this photo, we may reach the following conclusions. Lightning in a ball with dimensions of 6 - 8 cm was directed toward the roof of the meteorological station, on which there were many metallic objects. After reaching the roof, the lightning turned sharply downward, the radius of the curvature of the turn amounted to about 1.5 m. The lightning passed between two posts and turned toward a stand, on which there was a rain gauge. Luminescence of the lightning oscillated continuously, constantly decreasing

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[9] See Priroda, No. 4, 1957, page 113.

with each new flash. Simultaneously with pulsations, the lightning diameter increased by 20 - 30%, and its path somewhat twisted, while increase in luminescence was accompanied by a deflection of lightning from its trajectory upward by 10 - 20 cm. Five such deflections are noted on the photo, accompanied by an increase in luminescence and dimensions of the lightning. It is interesting that in the center of the lightning trace, an area with a diameter of about 1 cm, the luminescence of which is 2 - 3 times greater than in the rest of the lightning, may be clearly seen. Near the stand, the lightning veered sharply upwards, directed toward the metallic cover of the rain gauge with several sharp objects (on which electric field strength undoubtedly changed sharply). Short of the rain gauge by approximately a meter, the lightning gradually disintegrated over 20 - 30 cm. However, its central part, after momentarily dying out, shot forth in the form of sharp sparks for 30 - 40 cm to the metallic covering, after which it gradually extinguished. Pulsation frequency of this lightning undoubtedly amounted to around 3 - 5 cps.

Among photos of ball lightning made abroad, mention should be made of that done by B. Mattias and S. Bukhsbaum, in the above-mentioned article by K. Keyd (Figure 4). The photo was obtained in August, 1961, during heavy thunderstorms in Los Alamos. Ball lightning, as seen in the photo, appeared over trees, died out several times and flashed up again, leaving a broken trace. If we consider that the lightning moved from right to left, it had a maximum dimension of approximately 30 cm, with a speed of about 2 m/sec. On the first flare-up noted in the photo, the diameter of the ball increased in 0.1 seconds from 15 to 18 cm. After dying down at hundreds of units per second, the lightning flared anew to a diameter of 25 cm and in 0.5 seconds, decreased to 10 cm. The fourth flash, like the two preceding ones, occurred within hundreds of a second, but the fifth, barely noticeable flash lasted for only 0.3 seconds. If we consider that the duration of lightning corresponding to the photograph amounted to 1.5 seconds (during which the lightning died out for 0.3 seconds), then the impression is created that the photograph registered the final stage of ball lightning, in which in agreement with one of the hypotheses considered above, emission with spontaneous disappearance of lightning

Figure 4. Pulsating ball lightning, photographed during heavy thunderstorm in Los Alamos (photo by V. Mattias and S. Fukhsbaum; exposure time 5 minutes).

pulsates several times. On the assumptions made above, the pulsation frequency amounted to about 4 cps.

We shall present typical descriptions of ball lightning obtained from various eye witnesses of this interesting phenomenon. Ball lightning, observed during a light rain at approximately 19 hours 30 minutes during the summer

in the city of Yegor'yevsk by Ye. I. Knyazevaya, had dimensions of approximately 20 cm and luminescence of a light blue color. The lightning moved primarily in one direction, sinking to the earth and then rebounding. Children attempted to catch it, but it appeared to jump away from them by several meters. The lightning did not react to the iron covered slats of gateways: it quietly touched ground between them at an angle of 45° and immediately after contact with the /55
soil, sharply jumped upwards in a vertical direction. It then deflected to the right at an angle of 45° and disappeared without a trace, without causing any sort of destruction. According to the sketch, carefully made by Ye. I. Kniazevaya with oil paints, the lightning was in the form of a regular ball. Its luminescence somewhat decreased with an increase in distance from the center of the ball to the periphery, while the color changed from bright yellow at first to a greyish green and then to light blue. In the sketch, the transition from the pure bright yellow in the interior of lightning to its surface parts in the form of an envelope with a thickness of about 2 cm of bluish color can be seen.

In the same city on a summer evening, more ball lightning was observed. Clear blue in color, as regards luminescence, it was somewhat stronger than an electric light with a power of 200 watts. The lightning slowly moved upward, and after reaching the Earth's surface, jumped upward 3 - 4 m. After a fourth upward jump, the lightning moved upward smoothly and was obscured from view. The lightning did not react in the slightest to a willow tree standing nearby.

D. I. Kulagin followed an interesting case which occurred in Tashkent on the evening of 15 October 1967, when ball lightning was observed not during a thunderstorm, as usually occurs, but during a steady rain. Synoptic conditions on that day throughout the whole of Uzbekistan were characterized by an invasion of a cold front; for 24 hours everywhere there had been a constant rain with only short breaks. After careful inquiry of eyewitnesses (eight persons), it was determined that ball lightning was observed simultaneously with a squall, the motion of which is depicted in Figure 5. At 20 hours, 30 minutes local time, as before, there was a light rain, but it quickly changed to a heavy

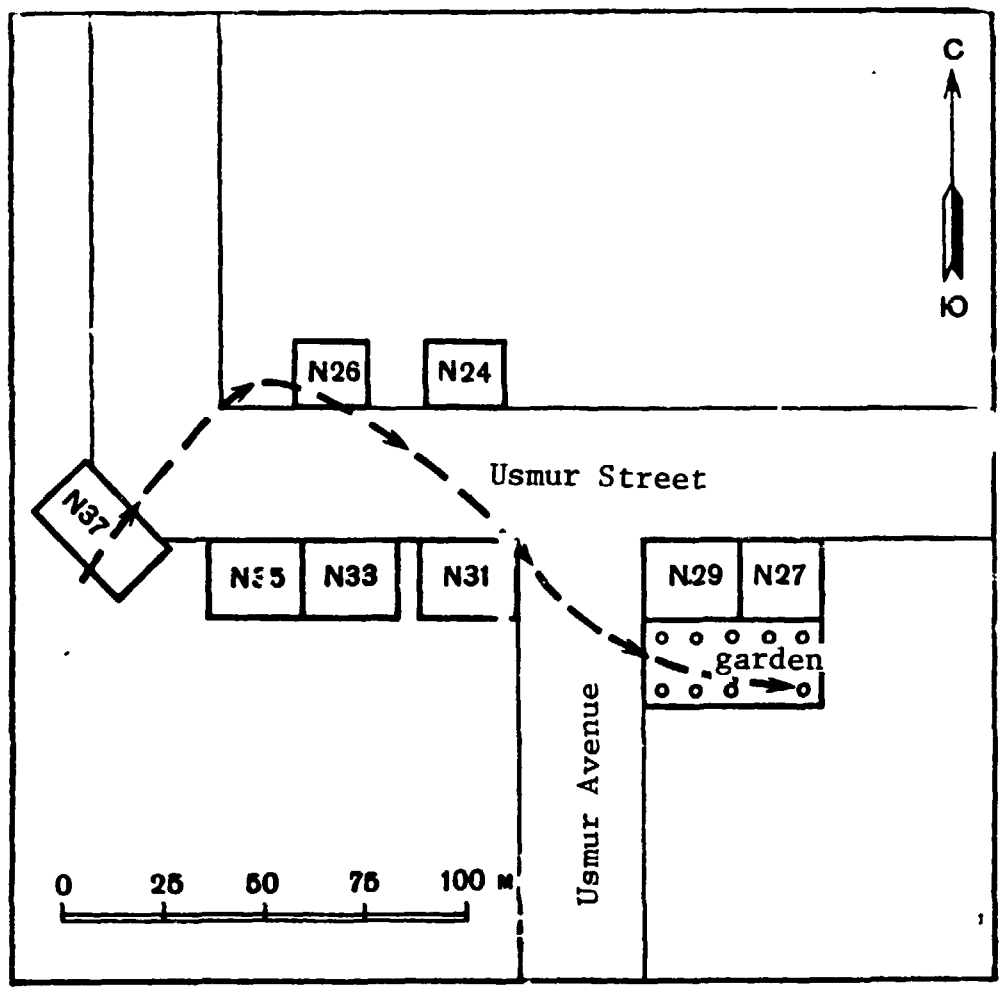

Figure 5. Chart of the motion of a squall and ball lightning during observation in Tashkent on the evening of 15 October 1967.

shower. First observation of the squall and lightning was made at the home at No. 37 Usmur Street, Chilanzarskiy region. Within several minutes after the rain ceased, the wind blew with hurricane force, which lasted approximately /56
10 seconds. At Home No. 37, it lifted and then overturned an iron roof and rafters. In the house on the other side of the street, No. 26, a fence and vineyard were overturned; at home No. 31, a hinged window was torn off (it was thrown about 30 m). Near home No. 29, a cherry orchard was uprooted. In

all these homes a deafening roar or strong crack was heard. From the window of home No. 37, clear, quite prolonged, pale green luminescence was seen, and from another window, flying luminous sparks of bluish color. From the window of home No. 26, blinding sparks, reminiscent of welding, were noted (the strong swirling sparks separated into smaller ones, as occurs in a nuclear reaction) and also clear bluish explosions (from another room). From home No. 31, a fiery ball was seen, circling over homes No. 29 and 27, or from another room, a small disk of bluish color, circling over the same homes. The resident of home No. 27, L. S. Ninko, who was in his garden observed that, along with a mighty wind from the neighboring garden at home No. 29, a fiery ball of 20 - 25 cm diameter smoothly moved through the air and then collided with some object (undoubtedly a tree), then exploded with a deafening boom. After this, all plants in the garden appeared to be destroyed, but apparently did not suffer serious effects.

Thus, from these data, it is possible to conclude that in approximately 10 seconds, relatively strong ball lightning with a diameter of about 25 cm, accompanied by a squall, on a meandering path, covered a distance of about 300 m (with an average speed of about 30 m/sec), and the entire phenomenon was local in nature in a zone about 10 m wide. Thus, inhabitants of homes No. 35, 24 and 33 hardly experienced any squall, did not hear the roar, and trees in the garden, at a distance of 2 - 3 m from the uprooted cherries, remained unharmed. The lightning emitted several little balls, which in turn, divided into bright sparks. D. I. Kulagin assumes that the observed lightning was formed as a result of ionization of air in a pluvial cloud, which arose as a local condensation in a system of nimbostratus clouds of type Nb, St, from which constant rain fell. The brief rain shower with large drops attests to the existence of such a condensation. In the same condensation, as the result of convective turbulent processes, a vortex was formed which tended toward the Earth's surface. Ball lightning was undoubtedly in the center of this vortex.

Very valuable observations of ball lightning were made by L. N. Solov'yev during the summer of 1955 in the city of Yur'yevets, Ivanovskaya oblast. There was strong thunder, and claps of lightning occurred almost simultaneously.

In the calm when there was scarcely any wind, from the street there resounded an exceptionally great clap of lightning, as if alongside the window. Unexpectedly, several seconds later, in a window with dimensions of 40 x 30 cm, there appeared and slowly floated into the room a weakly luminous pale violet ball, 1 - 8 cm in diameter. The form of lightning changed constantly; it first extended, then contracted in the direction of motion. The lightning quietly soared over the heads of two persons (apparently his son sitting on his lap) and went in the direction of a fig tree. It was clearly seen that the lightning freely passed between the leaves, contracting in the narrow areas and widening again. Then the lightning headed toward a loud speaker (a "record" type). When it was opposite the center of the speaker, an extraordinary loud explosion was heard, even by neighbors in other apartments. In the loudspeaker, the transformer was damaged — its covering, in the form of a coil, was reduced to tiny scarps of wire. No other harm at all was discovered. /57

Ball lightning was observed by four witnesses at 18 hours on May 23, 1962, during a strong thunder storm in the city of Belovo, Kemerovskaya oblast. The lightning assumed the form of a dazzling ball about 20 cm in diameter, in its path hitting a television antenna on the roof of a one-story wooden structure at a height of 10 - 12 m from the Earth. With a deafening clap, the lightning punctured the ceiling, burning the puncture along the edges, tore the electric register from the wall and broke it into little pieces, greatly damaged the television and broke a window. Also, the sewing machine was damaged (alongside it on the floor a depression was noted), an electric conduit about 30 m long was broken into little individual pieces, and plaster and electric lamps were damaged. On the wall, parallel to the electric wiring, varicolored spots were left, and a pile of newspapers caught fire. (A. K. Zhivopistsev, V. Pudov and others.) In the opinion of I. S. Stekol'nikova, this is very interesting.

Several witnesses observed ball lightning at 20 hours 30 minutes on July 10, 1962, in mining settlement No. 19/20 in the city of Gorovka. During the day, air temperature reached 30°; during the day it was humid, and toward evening, small rain clouds appeared from the north. A very light rain fell

quickly. Lightning in the form of a fiery ball with a diameter of 10 - 15 cm was noted near a solitary tree, then exploded accompanied by a strong roll of thunder. At 150 m from the explosion site, a sharp flare was seen, and on televisions near the place of observation, a short loss of image was noted (there was rapid flickering on the screen). Aside from the explosion of lightning, there was no thunder on that day. To those who heard it, this single discharge was unusual. On an overturned tree (a large acacia with a trunk diameter of about 25 cm) traces of strikes were noticed. From the base to a height of 3 m, the bark was completely stripped off. The trunk was broken into individual pieces (shredded). At a height of 3.5 m from the earth, the trunk was damaged in two places in small zones at a distance of approximately 30 cm from one another (this is the presumed area of interaction of lightning and wood). Soil at the base of the tree was badly torn up. The top of the tree was left practically intact and did not wither on the next day, although at a distance of 5 - 6 m from the base, scars were seen on it (in the form of notches near the trunk). It was observed that the main damage to the tree occurred 2 - 3 m below the height of the lightning at the moment of its explosion (Ye. P. Filozop, S. Kibkalo). As is known, trees with great moisture content in the trunk (poplar, elm, pear, acacia, etc.) preserve their foliage when struck by linear lightning, while other trees (oak) are completely stripped of leaves. Thus, harm inflicted in this instance by ball lightning was approximately like that from linear lightning.

Ball lightning is observed much more rarely in great cities, which may be explained by the presence of roofs, lightning rods and other objects. In this regard, the case of ball lightning in Moscow on 5 June 1964 is of interest. During the course of the day with a temperature of around 20° C and a southwest wind, rain fell several times, after which the sun shone. At approximately 15 hours 30 minutes, ball lightning penetrated through an opening in a window of a school situated on Orshanskaya Street, home No. 10. In the den on the fourth floor on different sides of a table sat director O. D. Kalinina and leader L. A. Vorob'yeva. Simultaneously with the appearance of the lightning, three of the senior students (Bulanov, Arina and Abramov) entered the room.

The lightning in the form of a clear scarlet ball with a diameter of 6 - 7 cm slowly floated past the telephone (during this, a strong crack was heard from it) and further over the table between the two persons. Then the lightning began to slowly rise upwards, then at a height of approximately 1.5 m, passed over the students and went into the corridor. The lightning continued to rise higher, and after reaching the ceiling, with an electric conduit of approximately 10 cm diameter, it exploded with a sharp deafening crack. The explosion was strong and very audible in the vestibule on the first floor. At the place of explosion along both sides of the pipe, two large spots of soot and smoke remained with a diameter of about a half meter; the surface of the conduit pipe was somewhat damaged. None of those present noticeably suffered with the exception of one of the women, sitting at the table on whose shoulder there was a painful burn, on an area of about 60 cm^2 (her hair was also singed). The odor of burning was very strong, overcoming other smells. It must be noted that in front of the school at that time there was a vacant lot about 0.2 km^2 in area, which could have facilitated penetration of lightning up to window level.

We have considered 45 cases of observations of ball lightning. This number may be sufficient to make certain general conclusions. Generalized results are presented in the table. From this material, it appears that ball lightning is a completely real and not especially rare phenomenon. Since, as a rule, observations were made by completely chance witnesses, information obtained does not make it possible to say anything about geographical distribution of ball lightning, about observations at high latitudes or at great heights. All data basically relate to quite densely populated areas. Nevertheless, individual cases were registered both at great heights from airplanes and in polar regions. As seen in the tables, the majority of observations (80%) occur during a warm time of the year (70% of them during the summer). However, ball lightning has also been registered during the winter. In analyzing the majority of cases, it is possible to conclude that ball lightning behaved autonomously (75%), changing course or properties depending upon hindrances encountered and other factors, and not guided by external influences (for example, radio emission of /58

TABLE: CHARACTERISTICS OF BALL LIGHTNING ACCORDING TO VARIOUS OBSERVATIONS

Characteristics of lightning	Number of observed cases	%
Observed during a warm time of the year	37	80
Exhibited autonomous qualities	33	75
Observed during thunder storm	31	70
Observed with rain (along with thunder)	36	80
Arose during a strike of linear lightning	8	20
Observed under city conditions	17	40
Quickly descended to earth	7	15
Rapidly rose upward	4	10
Moved horizontally	38	85
Freely floated in air	29	65
Revolved	4	10
Rebounded from surfaces	12	30
Simply settled	5	10
Attracted to conductors	16	35
Lifetime 1 - 2 minutes	32	70
Dimensions amounted to 10 - 30 sm	34	75
Speed of motion is less than 2 m/sec	30	70
Lightning emission pulsated	9	20
Lightning disappeared unnoticeably	13	30
Lightning exploded	24	55
Was the source of sound	28	60
Influenced radio communication	6	15
Produced disturbances	23	50
Injured people or animals	13	30

clouds). Seventy percent of ball lightning was noted in a thunder storm, although a significant number of observations are not immediately connected with thunder. About 20% of the observations, i.e., a sufficient number, are not connected with rain or snow. Formation of ball lightning immediately upon a shock of linear lightning is registered in 20% of all observations. Actually, such cases apparently could be significantly greater in number, since they simply are not accessible to observation. Ball lightning is frequently observed in cities (about 40%), which naturally may be explained primarily by the increased density of the populace, that is, by the greater probability of observation. It must be noted, however, that in very large cities or modern structures, there are only individual cases. Apparently, the probability of ball lightning penetrating to the level of soil or in a building is negligible due to the presence of a great quantity of grounded surfaces.

Ball lightning quite rarely falls to the earth rapidly (15%); still more rarely does it soar upward or perform a rotational motion (10%). In the majority of the investigated cases, lightning moved forward horizontally (85%). Moreover, in many observations (65%) it was clearly obvious that lightning freely floated in the air. Ball lightning much more frequently recoils from surfaces (30%) than simply settles on them (about 10%) and rarely is attracted to grounded conductors. It goes without saying that the number of cases, when ball lightning is attracted to conductors, could be even significantly greater than 35%, since such objects are encountered much more rarely than trees, fences, walls and other ordinary obstacles. If we consider that only about 30% of all hindrances are accounted for by conductors, then in practically all cases, ball lightning was attracted to them. This undoubtedly indicates the electrical nature of ball lightning.

In the majority of observations (70 - 75%) dimensions of the lightning amounted to 10 - 30 cm. The longevity was 1 - 2 min, while the rate of motion did not exceed 2 m/sec. However, in individual cases, very small lightning was observed (diameter of 2 - 3 cm), while longevity exceeded 2 minutes. Sometimes ball lightning shifts with a great speed (up to 0.5 km/sec).

Lightning frequently disappears unnoticeably (around 30%), but much more frequently explodes (about 50%). In individual cases (about 20%) lightning emission pulsated. If, however, we disregard observations when lightning exploded under the influence of a number of factors, that is, did not disappear voluntarily, then we must consider the cases with pulsations to be around 45%, and if we exclude the cases when lightning was hidden from view, then pulsation occurred in 80 - 90% of the cases.

Apparently, thanks to the high temperature of the material, ball lightning is the source of sound oscillations and radiowaves, although — due to the accidental character of such observations — influence on radio communication or electric meters was registered only in individual instances. Undoubtedly, ball lightning emits even ultraviolet rays. The emission by ball lightning of ionizing (roentgen) radiation remains an open question, although in one case, the power of a dose amounting to about 1 roentgen/min (converted to a distance of 30 cm) was registered. Therefore, recalling occasional cases in which witnesses close to the lightning suffered heavy damage, it may be explained by radiation damage. However, in the majority of cases considered above, witnesses who feel well even at the present time make it impossible to establish such a connection. The most ordinary illnesses, including lethal outcomes, appear to be the result of the action of shock waves or electric shocks and occur upon explosion of /59
lightning (about 30%). Explosions of lightning in almost all cases produce various types of damage, often causing great harm.

From this material, it is possible to make only a few comments on the validity of one or another hypothesis. In agreement with the hypothesis of the superconductive condensate, very heavy ball lightning must basically fall to the surface of the Earth. According to the hypothesis of the toroidal vortex, lightning with a density on the order of 1 g/cm^3 also must fall to the earth and rotate. Meanwhile, as is obvious from the table, in the majority of cases, lightning freely floats in the air or moves horizontally, which naturally does not confirm these hypotheses. Revolving motions occur relatively infrequently, which does not agree with the toroidal vortex hypotheses (rotation of lightning is perhaps explainable by other hypotheses). Finally, not a single

case was registered when after omission of ball lightning, there rapidly occurred an explosion in the same place as linear lightning. At the same time, there are frequent cases of generation of ball lightning after the impact of linear lightning, although the basic discharge from the cloud could have already occurred.

The ability of ball lightning to freely float in air undoubtedly indicates that the average density is close to the density of air, but this apparently does not agree with the hypothesis of a superconductive condensate. Attraction to conductors attests to the presence of an electrical charge in ball lightning, which corresponds to many hypotheses. However, its ability to pulsate with spontaneous disappearance may be explained more satisfactorily by the hypothesis of macro-ionic formations. According to the character of the explosions, it is possible to conclude that in this regard ball lightning is close to ordinary material. Thus, in the presence of hindrances or hermetization of lightning, the power of the explosions significantly increases. At the same time, explosions of lightning in a free atmosphere are observed comparatively rarely. Ball lightning is very dangerous, in connection with which, the question of defending humans, aircraft, warehouses of combustible materials, etc. from it is important. Since the electrical nature of ball lightning is not subject to doubt (despite several contradictions to this hypothesis) some general measures of security are analogous to precautions against shock from linear lightning. However, this question remains controversial. In the literature, the following cases of successful combats with ball lightning are often mentioned. In August, 1936, ball lightning with a diameter of 15 - 20 cm appeared during heavy thunder showers during a strike of linear lightning on an iron chain, after which it penetrated a dwelling and rolled under a wooden bench. A man in the vicinity was able to combat it by several strikes at the lightning with a board, after which only a sharp odor remained. It is impossible to recommend this in all cases. From the point of view of the hypothesis of macro-ionic formations, a similar situation in which ball lightning is subjected to mechanical influence is extremely dangerous. Such an action will hasten emission of energy from the lightning or limit the possibility of its moving, causing an

explosion. In this case, if ball lightning is directed toward a man, the author of this hypothesis recommends using some sort of nonmetallic object, quietly displaying it on the path of the ball lightning, which may prevent damage[10].

From the above material, it is obvious that nature of ball lightning will continue to be the subject of discussion and scientific study for quite some time. However, it is scarcely possible to doubt that the problem will be solved by modern science. Undoubtedly in the very near future, conditions will be produced in laboratories in which ordinary ball lightning will be formed in the lower layers of the atmosphere, and also intensive research on natural ball lightning will be unfolded through radiophysical and rocket technology. The united efforts of physicists, chemists, and meteorologists will not only reveal the structure and properties of ball lightning, but will also effectively use this natural phenomenon in scientific research and technology.

Biography

Mikhail Timofeyevich Dmitriyev heads the Laboratory of Physical Chemistry and Radiological Research in the Institute of General and Communal Hygiene, USSR Academy of Sciences. His main scientific interests are in physics of the atmosphere and radiation chemistry of the air. In this area, he has published about 200 scientific studies. Moreover, M. T. Dmitryev carefully collects and investigates observations of ball lightning, to which several of his articles are devoted.

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(10) For more details on means of defending airplanes, storehouses of combustibles and also pedestrians, from ball lightning, see the journal, Aviatsiya i kosmonavtika, No. 9, 1970, page 36.

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